The Belle Silicon Vertex Detector

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Abstract

The silicon vertex detector of the Belle experiment has been built to provide the vertex information of B meson decays at the KEKB accelerator. It consists of three cylindrical layers of double sided, double metal silicon sensors read out by VA1 chips. The analog signals are transmitted to a system of fast analog-to-digital converters and are reduced on a system based on Motorola Digital Signal Processors. Performance during the initial data taking period and a brief description of the upgrade plan are also presented.

Key words: Belle, KEKB, B-factory, Silicon vertex detector

1 Introduction

The Silicon Vertex Detector (SVD) of the Belle experiment [1] at the KEKB accelerator [2] has been built to provide vertex information from precision measurements of charged tracks in the vicinity of the interaction point. Because the KEKB is an asymmetric e^+e^- collider with 8 GeV e^- and 3.5 GeV e^+ beams, a pair of B and $\overline{B}$ mesons, produced nearly at rest at the center of mass system (CMS), is boosted along the e^- beam direction with a Lorentz boost factor of $\beta\gamma = 0.425$. Therefore, in designing the SVD a special emphasis is placed on the precise measurement of the z (boost direction) coordinate. The typical separation between B and $\overline{B}$ decays at the KEKB is $\sim 200~\mu$m and we find, based on the simulation, the z resolution of $\sim 100~\mu$m in B meson decay vertex measurement is sufficient to detect a possible asymmetry in the proper time interval distribution for decays of $B^0 - \overline{B^0}$ pairs. This asymmetry signals CP-violation in the B meson system when one of the neutral B mesons decays to a CP eigenstate.

The SVD consists of three concentric cylindrical layers of silicon sensors with two orthogonal-coordinate readouts. The vertex resolution for low momentum tracks is dominated by multiple scattering in a material before the SVD plus the first SVD layer. Figure 1 displays the geometrical layout of the SVD. The radii of the three layers are 30 mm, 45.5 mm and 60.5 mm. The SVD covers the polar angle range of $23° < \theta < 139°$ corresponding to 86% of the solid angle in the CMS. There installed is a 20.5 mm-radius beryllium beampipe with two 0.5 mm-thick walls allowing helium gas flow to cool the beampipe. A 20 μm gold foil is glued on the inner concentric cover consisting of carbon-carbon material to protect the SVD from soft Xrays produced in the beampine. The material before the first SVD layer amounts to 0.95% of 1 radiation length.

The first layer is formed from 8 "ladders", each of which contains two double-sided silicon strip detectors (DSSDs) which are read out separately. The second layer is formed from 10 ladders, each containing 3 DSSDs. Two of 3 DSSDs are connected to make a single two-sensor unit, in which p-strips on one DSSD are wire-bonded to n-strips on the other DSSD to minimize a noise in a channel. The third layer is formed from 14 ladders, each containing 2 two-sensor units. A full ladder consists of DSSDs, aluminum nitride hybrids at each end, glued with an aluminum nitride heat sink containing two heat pipes and CFRP reinforced boron nitride ribs glued across DSSDs and the heat sink, as shown in Fig. 2. The DSSD, HPK S6936, was originally fabricated for the DELPHI vertex detector by Hamamatsu Photonics. It has an active area of 54×32 mm^2 with a thickness of 300 μm. The strip pitch for a p(n)-side is $25(42)\mu$m and the readout pitch is $50(82)\mu$m. This DSSD contains integrated coupling capacitors and, therefore, the strips are AC-coupled to preamplifiers. It utilizes a double metal structure to read out n-strips. The total number of readout channels of the SVD is 81920. A bias voltage of 75V is supplied on n-side.

Each hybrid is made by gluing two identical aluminum nitride boards, each containing five 128-channel VA1 chips [3] providing 640 readout channels per board. The VA1 chip fabricated by 1.2 μm feature size process contains preamplifiers, shapers and track-and-hold circuits that capture the analog pulse-height information of each channel. The peaking time of the shaper is set to 1.0 μs to match the trigger latency. When the system switched from track-to hold-mode the stored analog information for each channel is sequentially routed via an on-chip analog multiplexor to a system of fast analog-to-digital converters (FADCs) [4]. Event buffering and zero data suppression are performed using Motorola Digital Signal Processors (DSPs) in the FADC module.

2 Basic Performance

The dE/dX distributions of minimum ionizing particles for p-side and n-side, together with the correlation between signals from two sides are shown in Fig. 3. The dE/dX values are calculated by summing all signals (above threshold) which belong to the same track and by normalizing to the same track length (i.e., 300 μm). The signal peaks at $\sim 18,800e$ and $\sim 19,200e$ for p-side and n-side, respectively, while the electronics noise is found to be $\sim 550e$ for p-side channels, $\sim 1000e$ for n-side channel and $\sim 1100e$ for p-n combined channels in which a p-strip and an n-strip are connected. Therefore, Signal-to-Noise (S/N) ratio is well above 10. The strip yield for each layer is found to be 98.8%, 96.3% and 93.5% for 1st, 2nd and 3rd layers, respectively. The loss of strips includes failure of hybrids and a few failed coupling capacitors. Since the installation in August 1999, the SVD has been functioning stably. The occupancy of the SVD is $\sim 1\%$ at the luminosity of $1.2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. For hadronic events we find 97% of tracks reconstructed by the Central Drift Chamber (CDC) have corresponding hits in the SVD. The internal alignment of the DSSDs and the SVD-CDC relative alignment have been performed using cosmic rays taken with and without beams in the KEKB. In order to illustrate the so-far achieved alignment we summarize in Table 1 resolutions of track helix parameters[1] compared with the values for the perfect alignment, predicted by Monte Carlo simulation. We note that the $dz, \tan \lambda$ resolutions are mostly determined by the SVD internal alignment performance, while the $d\rho, \phi_0, \kappa$ resolutions depend on the CDC track resolutions as well.

Figure 4 shows impact parameter resolutions, $\sigma_{r\phi}, \sigma_z$, for $r\phi$ and z directions measured using cosmic rays, Bhabha events and $\gamma\gamma \to e^+e^-, \pi^+\pi^-\pi^+\pi^-$ processes. We obtain

$$\sigma_{r\phi} = \sqrt{(21)^2 + \left(\frac{69}{p\beta \sin^{3/2} \theta}\right)^2} \ \mu\mathrm{m}; \quad \sigma_z = \sqrt{(39)^2 + \left(\frac{51}{p\beta \sin^{5/2} \theta}\right)^2} \ \mu\mathrm{m},$$

where p and β are momentum in GeV/c and velocity divided by c of the particle, and θ is the polar angle from the beam axis. The resolution in a measurement of the distance between two z vertices of leptons originating from a J/ψ particle can also infer the resolution of the z coordinate measurement. Here, each z vertex is calculated by finding an intersection between a lepton track and the beam axis. We find $\sigma_{\Delta z(\ell^+\ell^-)} = 138\mu$m, while Monte Carlo predicts 112μm.

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[1] A charged particle track is expressed as: $x = x_0 + d\rho \cos \phi_0 + \frac{\alpha}{\kappa}[\cos \phi_0 - \cos(\phi_0 + \phi)]$, $y = y_0 + d\rho \sin \phi_0 + \frac{\alpha}{\kappa}[\sin \phi_0 - \sin(\phi_0 + \phi)]$, $z = z_0 + dz - \frac{\alpha}{\kappa}(\tan \lambda)\phi$, $\alpha \equiv 1/cB$(Tesla).

3 Physics Examples

In order to demonstrate the overall performance of the SVD, we present preliminary results of D and B meson lifetime measurements based on the first 0.25 fb^{-1} data collected during the initial data taking period [5]. We reconstruct D^0 mesons in the decay mode $D^0 \to K^- \pi^+$. Charged tracks forming a D^0 candidate are required to be well-reconstructed in the tracking system and to originate from a common vertex. Kaons are positively identified in the particle ID system [6]. In order to avoid bias due to B meson lifetime, D^0 mesons originating from B mesons are removed by requiring D^0 mesons have a minimum momentum of 2.5 GeV/c in the $\Upsilon(4S)$ rest frame. Figure 5(a) shows the invariant mass distribution of $D^0 \to K^- \pi^+$ decays. By fitting the distribution with a Gaussian for the signal plus a linear function for the background, we find the width of the signal distribution to be 7.6 ± 0.2 MeV/c and the number of signal events to be 1730 ± 50. The background fraction is calculated from the same fit and is about 10% under a signal peak (the region within $\pm 3\sigma$).

As illustrated in Fig. 5(b) the lifetime of the charmed meson is computed from the flight distance between the reconstructed D^0 vertex and the interaction point(IP) determined for each KEKB beam fill. The profile of the IP is known to have, from the machine optics and the beam size monitoring information, $\sigma_z \sim 4$ mm along the beam direction (z), and $\sigma_x \sim 100$ μm, and $\sigma_y \sim 5 - 10$ μm in the direction perpendicular to the beam direction. The D^0 flight length is measured in the xy plane to take advantage of the small IP size in the plane. The projected decay length ℓ_{decay}^{xy} of the D^0 meson is calculated from the D^0 momentum $\mathbf{p}_{D^0}^{xy}$, the D^0 decay vertex $\mathbf{r}_{D^0}^{xy}$, and the D^0 production point $\mathbf{r}_{IP}^{xy}$ reconstructed by extrapolating the D^0 momentum back to the IP profile: $\ell_{decay}^{xy} = (\mathbf{r}_{D^0}^{xy} - \mathbf{r}_{IP}^{xy}) \cdot \mathbf{p}_{D^0}^{xy}/|\mathbf{p}_{D^0}^{xy}|$. The proper time t is, then, calculated using the D^0 mass, m, as $t = (m/c)(\ell_{dec}^{xy}/|\mathbf{p}_{D^0}^{xy}|)$. The D^0 meson lifetime is extracted from the proper-time distribution with an unbinned maximum likelihood method. The detector resolution is mostly described by a single Gaussian with a small correction for events which might have undergone a hard multiple Coulomb scattering and/or have wrong CDC-SVD hit associations in the track reconstruction program. Figure 6 shows the fit to the proper time distribution. The preliminary result for the lifetime of D^0 meson is 405.3 ± 13.3 fs, where the error includes only the statistical error. This is in good agreement with the PDG value of 415 ± 4 fs.

The B meson lifetime is extracted from the measurement of the separation of B and $\bar{B}$ decays, Δz, in the z direction. We first reconstruct $B^0 \to D^{*-} \ell^+ \nu$, where D^{*-} decays to $\overline{D^0} \pi^-$ followed by either one of $\overline{D^0} \to K^+ \pi^-$, $K^+ \pi^- \pi^0$, $K^+ \pi^- \pi^- \pi^+$ decays. The decay vertex of B^0 is determined using the reconstructed $\overline{D^0}$ momentum and the lepton (ℓ^+) track. We, then, determine the

$\overline{B^0}$ decay vertex requiring all the remaining tracks in the same event, except for tracks originating from K_S decays and tracks with large impact parameters, form a common vertex. Figure 7(a) illustrates the vertex reconstruction of $B-\bar{B}$ events. The distribution of Δz with the fit result is shown in Fig. 7(b). The fitted function consists of the expected Δz distribution smeared with the detector resolution. We obtain the result of $\tau_{B^0} = 1.82 \pm 0.28$ ps, while the resolution in Δz is found to be $\sigma = 146 \pm 47$ μm. The result is consistent with the PDG value of $\tau_{B^0} = 1.56 \pm 0.04$ ps.

4 Upgrade Plans

The current SVD readout chips have limited radiation tolerance. The 1.2 μm-technology VA1 chip is not based on a radiation-hard technology and stops functioning after a γ-ray dose of ~ 200 krad. With the current radiation level observed at the KEKB, this corresponds to an integrated luminosity of ~ 8 fb^{-1}. We have been developing a frontend IC which stands radiation dose of more than 1Mrad by taking advantage of the thinner gate-oxide layers used in sub-micron CMOS processes. Because the threshold shift in a MOS transition scales as the square of the thickness of the gate oxide layer, which in turn is proportional to the FET channel width or equivalently to the feature size of the process being used, one expects the radiation tolerance of the IC scales as the inverse square of the feature size. One expects that a 0.5 μm process IC is four times more radiation-tolerant than a 1.0 μm process IC. We have fabricated two versions of VA1 chips, one with AMS 0.8 μm technology and the other with AMS 0.35 μm [7]. Figure 8(a) shows gain versus radiation dose for AMS 0.8 μm technology VA1. The gain decrease rate is found to be -0.06%/krad. Figure 8(b) shows the equivalent noise count versus radiation dose. Based on these measurements we conclude the 0.8 μm VA1 chips are radiation tolerant up to ~ 1Mrad. The new SVD built with these VA1 chips is scheduled to be installed in summer 2000. The AMS 0.35 μm VA1 exhibits the excellent radiation hardness as shown in Fig. 9. It is tolerant up to 20 Mrad. The SVD based on this 0.35 μm VA1 chips is also being planned.

5 Conclusion

We have successfully built the SVD for the Belle experiment at the KEKB. Preliminary measurements of lifetimes of D^0 and B^0 mesons show it is performing as designed. We have developed radiation-hard VA1 chips, based on a sub-micron process technology, which will be applied to the immediate upgrade of the SVD.

6   Acknowledgments

References

[1] Belle Collaboration, Technical Design Report, KEK Report 95-1, 1995.

[2] KEKB B Factory Design Report, KEK Report 95-7, 1995.

[3] E. Nygard *et al.*, Nucl. Instrm. and Meth. **A301**(1991)506. O.Toker *et al.* Nucl. Instrm. and Meth. **A340**(1994) 572.

[4] M. Tanaka *et al.*, Nucl. Instrm.and Meth. **A432** (1999)422.

[5] H. Aihara, "Physics Results from Belle," Proceedings of the 3rd International Conference on B Physics and CP Violation, December 3-7, 1999, Taipei, Taiwan.

[6] T. Iijima, "Kaon Identification in Belle," *ibid.*

[7] M. Yokoyama, "Test results of VA1 fabricated by sub-micron technology," This proceedings.

Table 1: Track helix parameter resolutions compared with Monte Carlo predictions for perfect alignment

	$d\rho(\mu m)$	ϕ_0 (mrad)	$\kappa(10^{-3})$	$dz(\mu m)$	$\tan\lambda(10^{-3})$
Data	28.0	0.747	2.63	42.1	0.973
Perfect (MC)	19.4	0.503	1.73	34.4	0.891

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Backward   Forward

139°   **23°**

IP
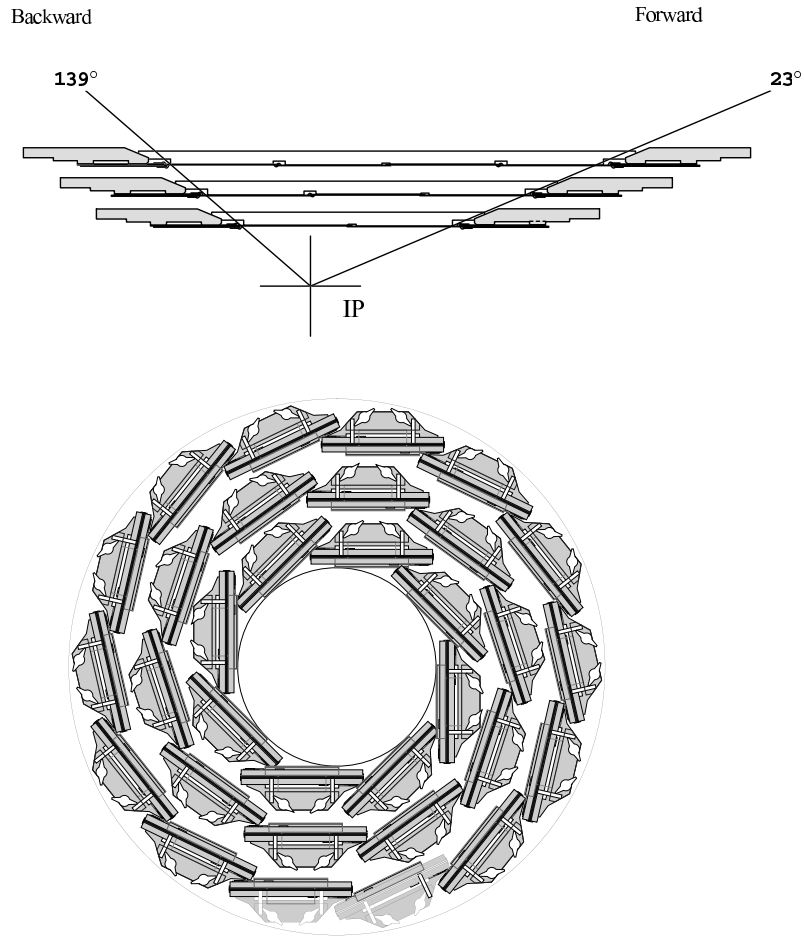
Layer 1: r=30.0mm, offset=9.5mm, 8 ϕ, 2z
Layer 2: r=45.5mm, offset=8.5mm, 10 ϕ, 3z
Layer 3: r=60.5mm, offset=12.5mm, 14 ϕ, 4z
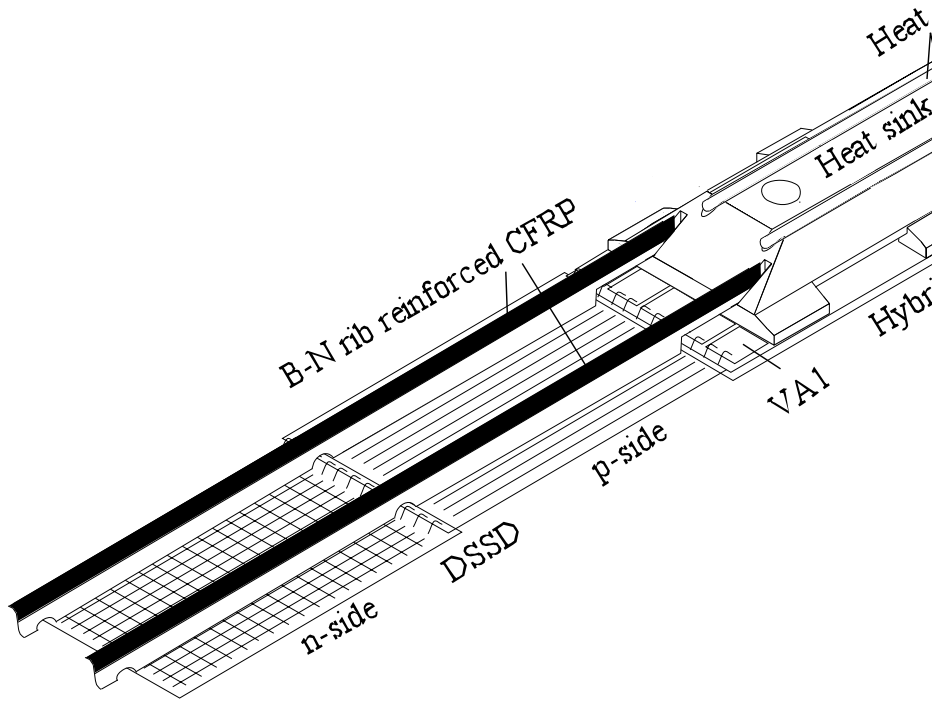
Fig. 1. Geometrical layout of the Belle SVD

Fig. 2. Construction of the SVD ladder. In order to form a two-DSSD unit, n-strips of one DSSD are wire-bonded to p-strips of the other.
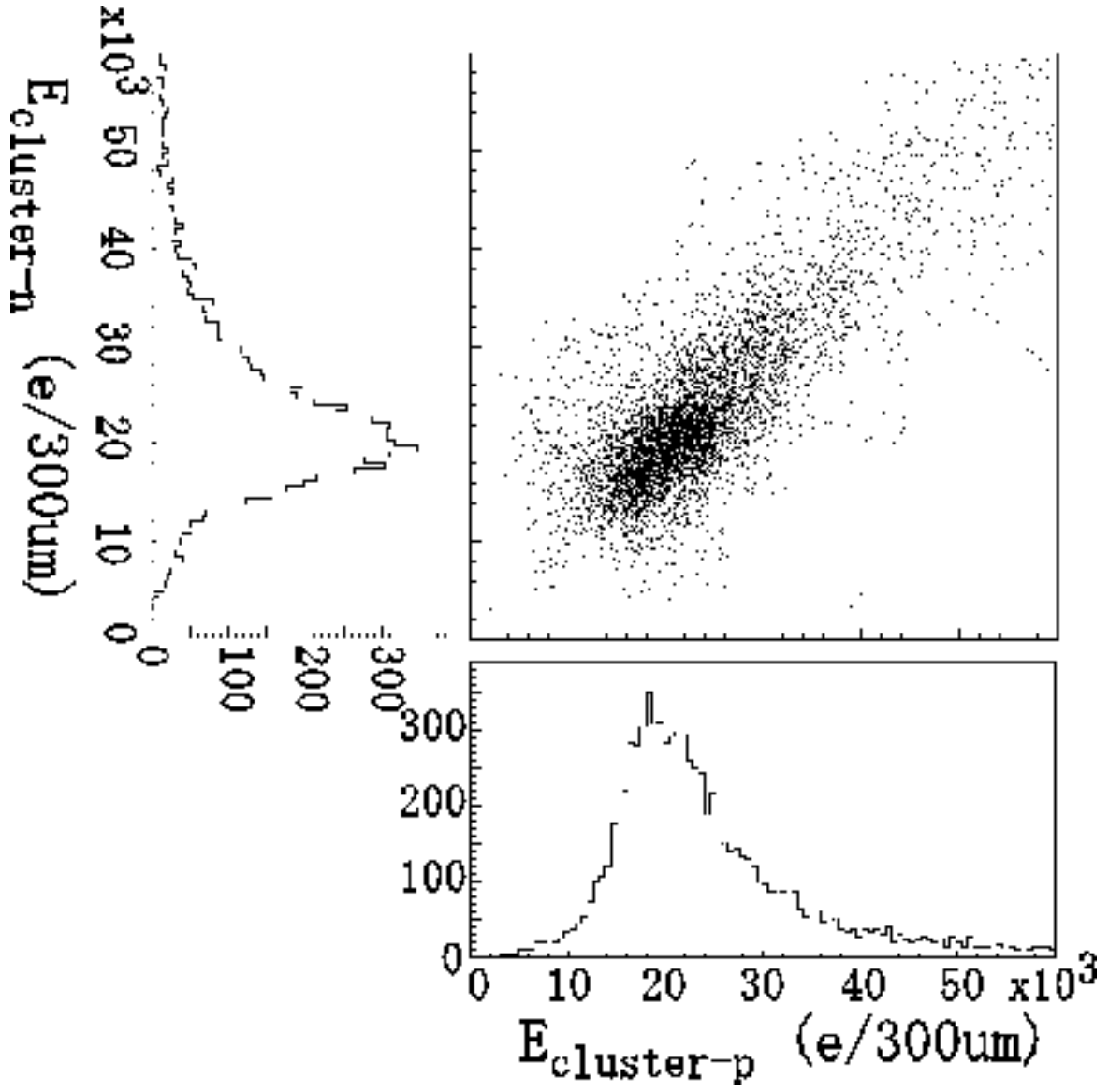
Fig. 3. dE/dX distributions per 300 μm-thick silicon of minimum ionizing particles given in units of electrons.
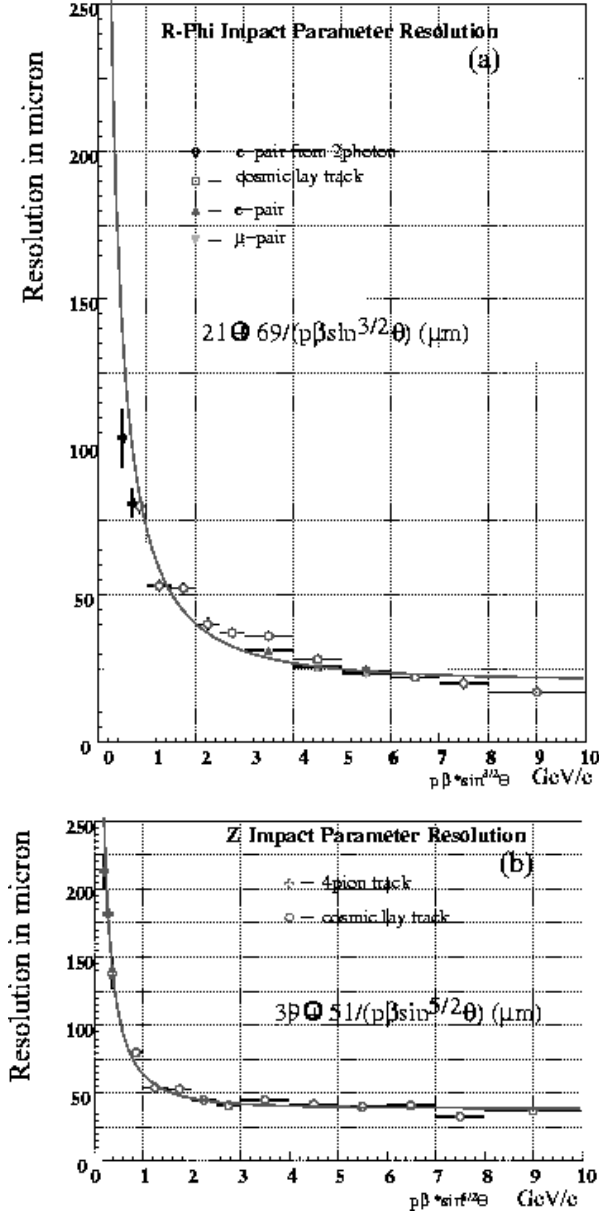
R-Phi Impact Parameter Resolution

(a)

Resolution in micron

250

200

150

100

50

0

e — pair from 2photon
cosmic ray track
e–pair
μ–pair

$21 \oplus 69/(p\beta \sin^{3/2}\theta)$ (μm)

$p\beta * \sin^{3/2}\theta$ GeV/c

0   1   2   3   4   5   6   7   8   9   10

Z Impact Parameter Resolution

(b)

Resolution in micron

250

200

150

100

50

0

★ — 4pion track
○ — cosmic ray track

$39 \oplus 51/(p\beta \sin^{5/2}\theta)$ (μm)

$p\beta * \sin^{5/2}\theta$ GeV/c

0   1   2   3   4   5   6   7   8   9   10

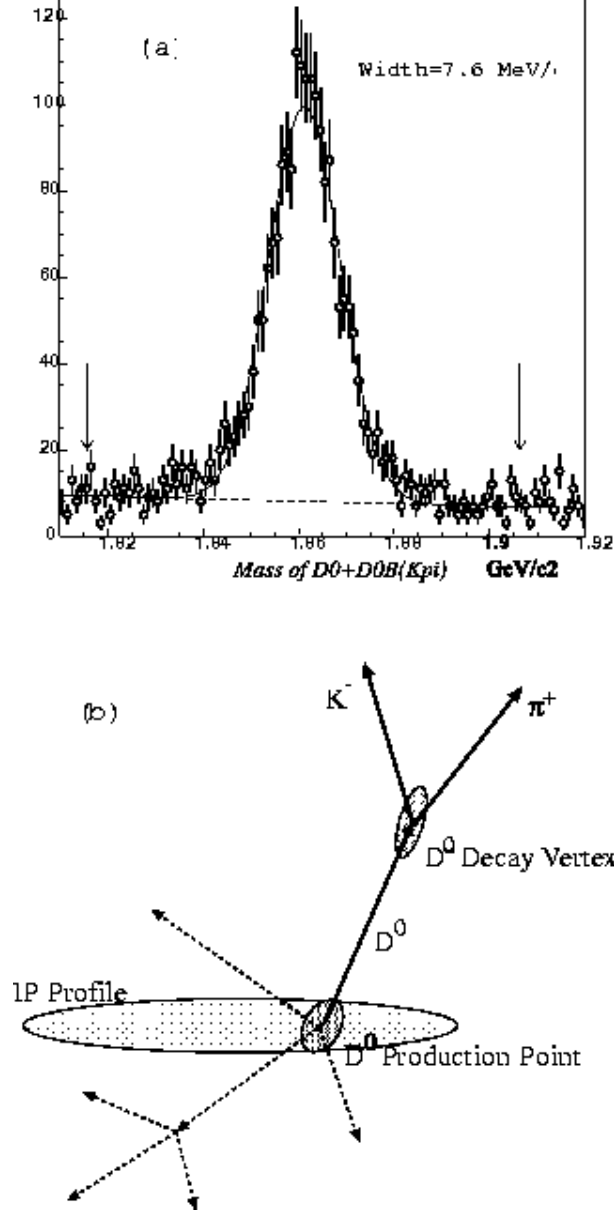Fig. 4. Impact parameter resolutions for (a) $r\phi$ and (b) z directions

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Fig. 5. (a)Invariant mass distributions of $D^0 \to K^-\pi^+$ decays. (b)Illustration to show how the D^0 meson flight length is reconstructed in the plane perpendicular to the beam axis.
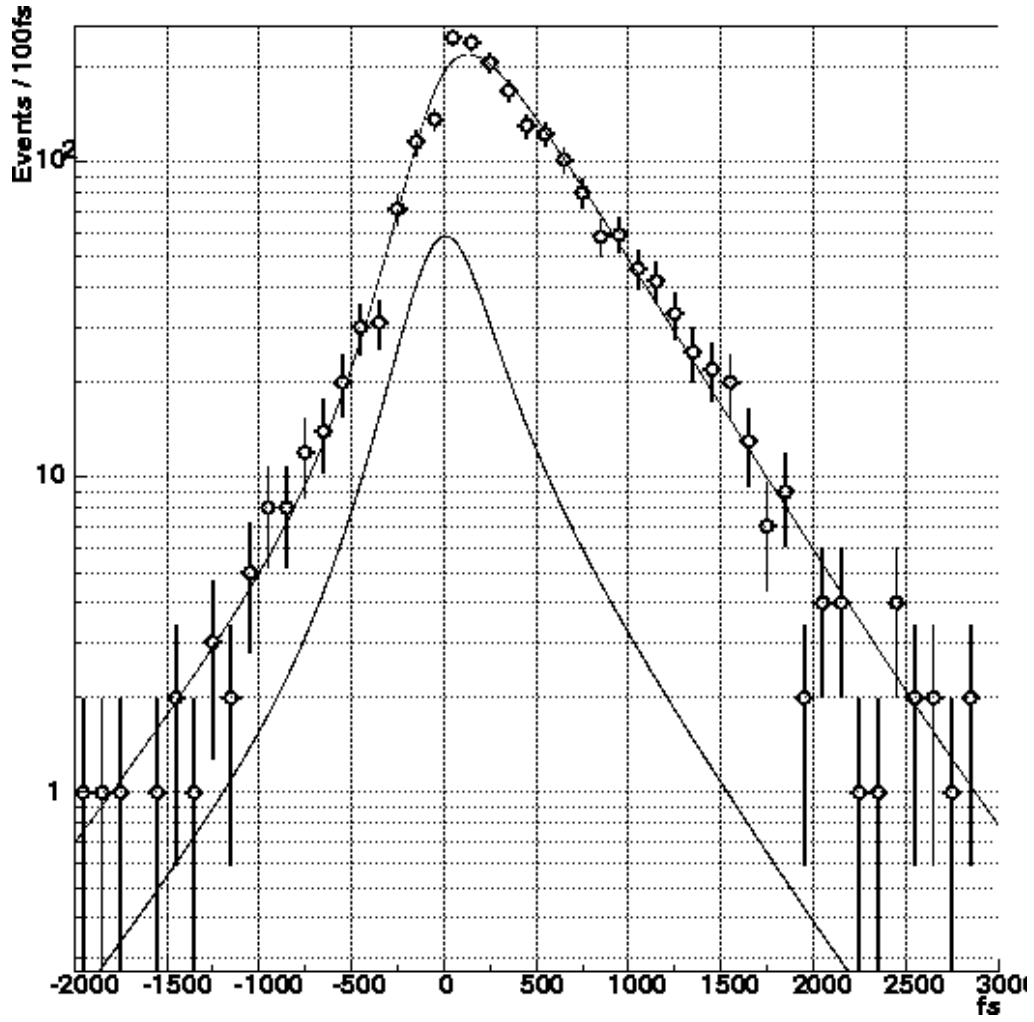
12

Fig. 6. The proper-time distribution of the D^0 mesons superimposed with the fit result. The solid line with data points is the overall fit result and the solid line without data points indicates the contribution from the background.
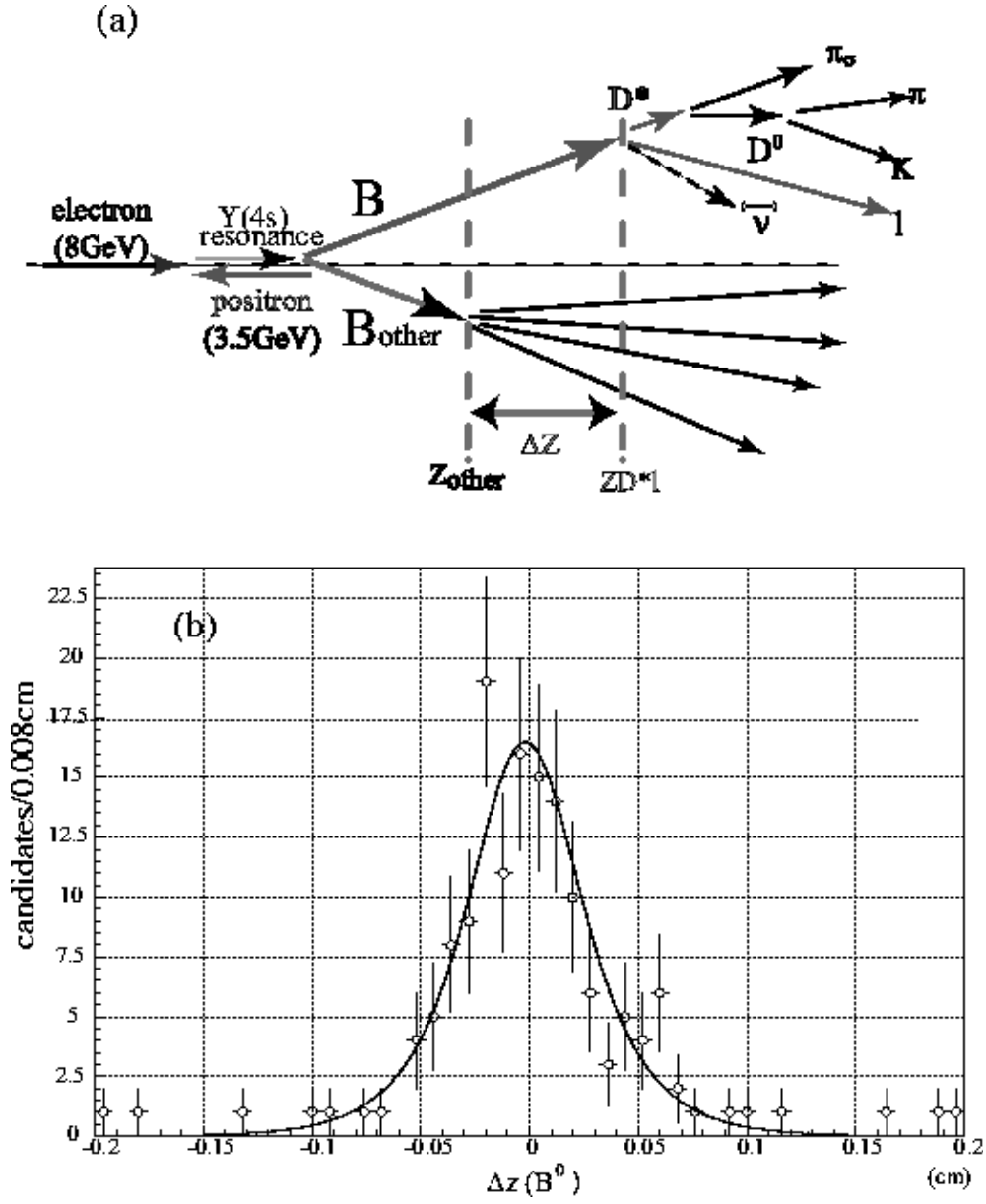
13

(a)

electron
(8GeV)

Υ(4s)
resonance

positron
(3.5GeV)

B

B_{other}

D^*

π_s

D^0

π

$\overline{\nu}$

K

1

ΔZ

Z_{other}

Z_{D^*1}

(b)

candidates/0.008cm

22.5
20
17.5
15
12.5
10
7.5
5
2.5
0

-0.2   -0.15   -0.1   -0.05   0   0.05   0.1   0.15   0.2

$\Delta z (B^0)$

(cm)

Fig. 7. (a) Illustration of reconstruction of B and $\bar{B}$ decay vertices. (b) Separation of B and $\bar{B}$ decay vertices in the z direction.
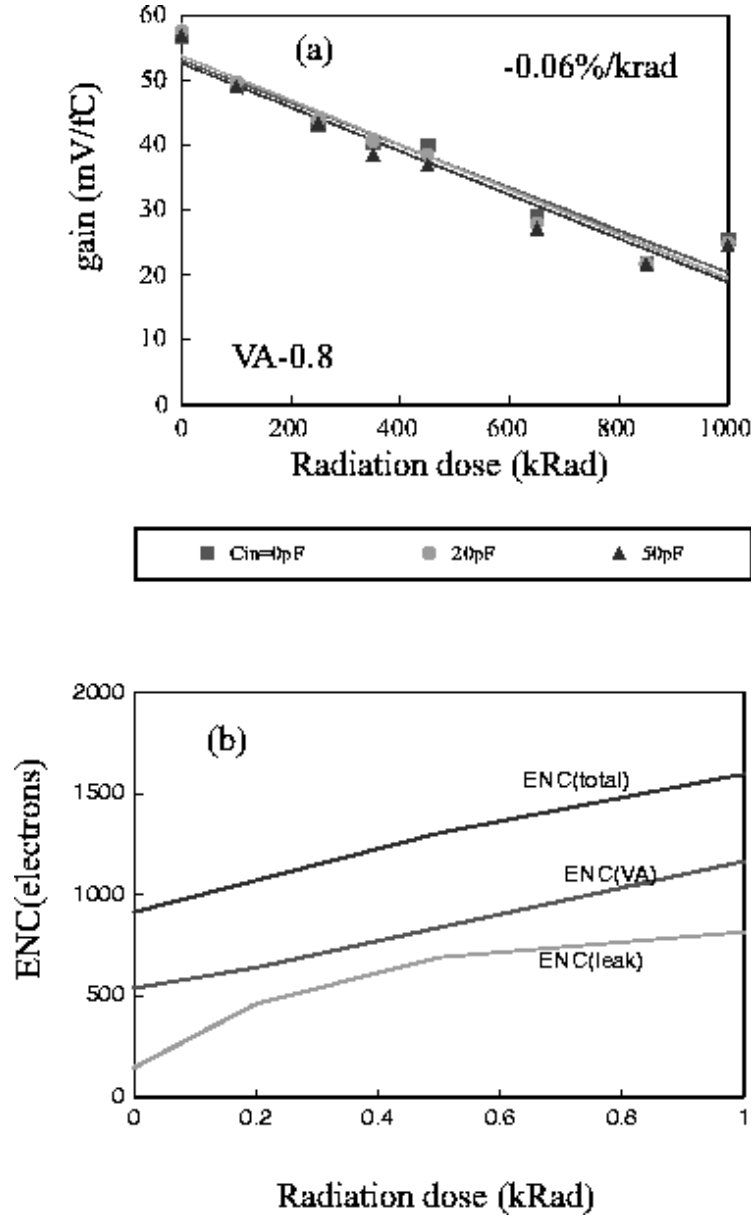
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Fig. 8. (a) gain versus radiation dose and (b) equivalent noise count (ENC) versus radiation dose for AMS 0.8 μm process VA1 chip.

Gain vs. radiation dose (Cin=20pF)

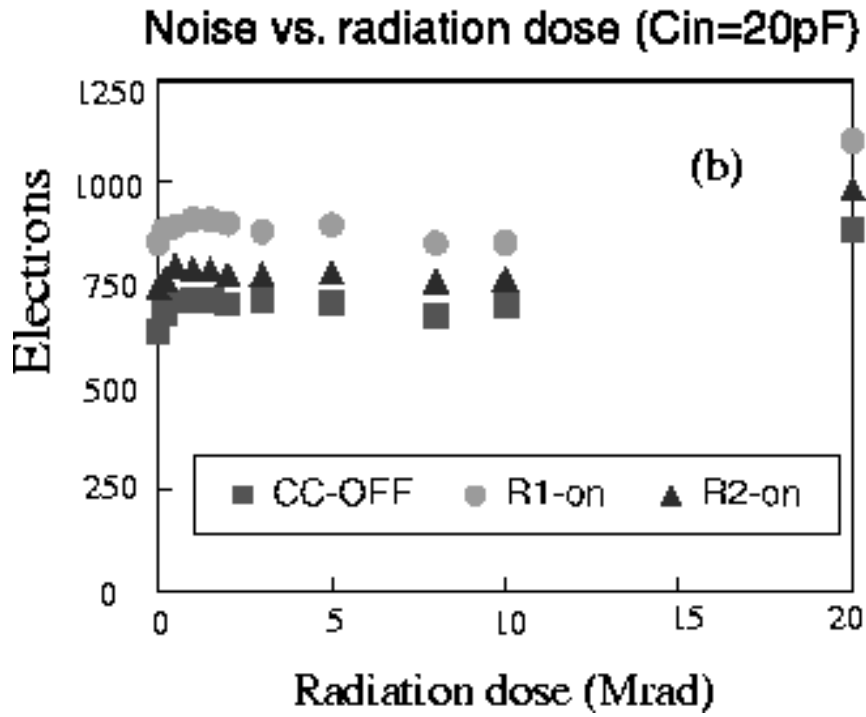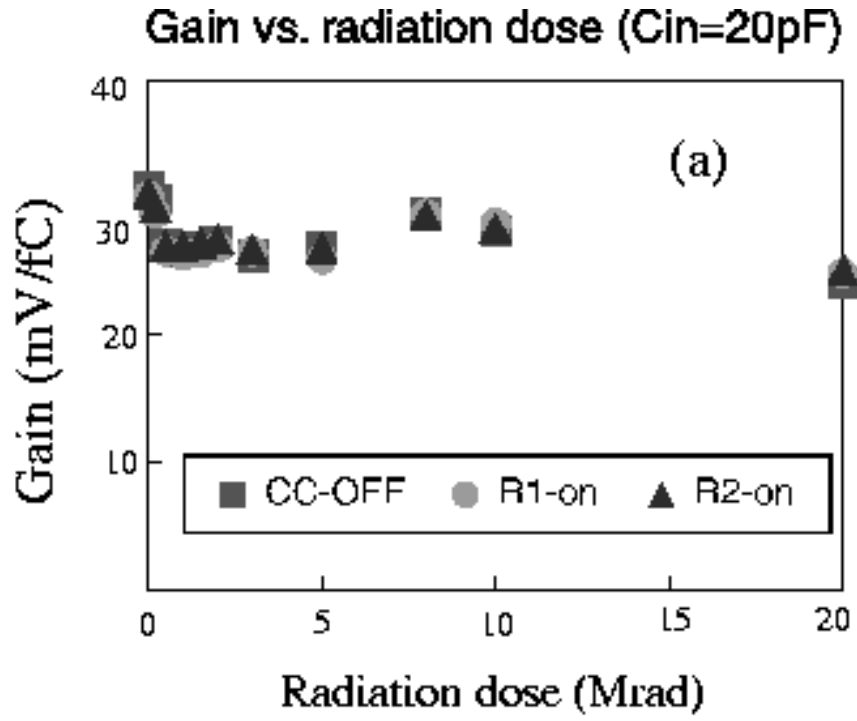## Noise vs. radiation dose (Cin=20pF)

Fig. 9. (a) gain versus radiation dose and (b) equivalent noise count (ENC) versus radiation dose for AMS 0.35 μm process VA1 chip.